



+5V PRECISION VOLTAGE REFERENCE REGULATOR AND THERMOMETER

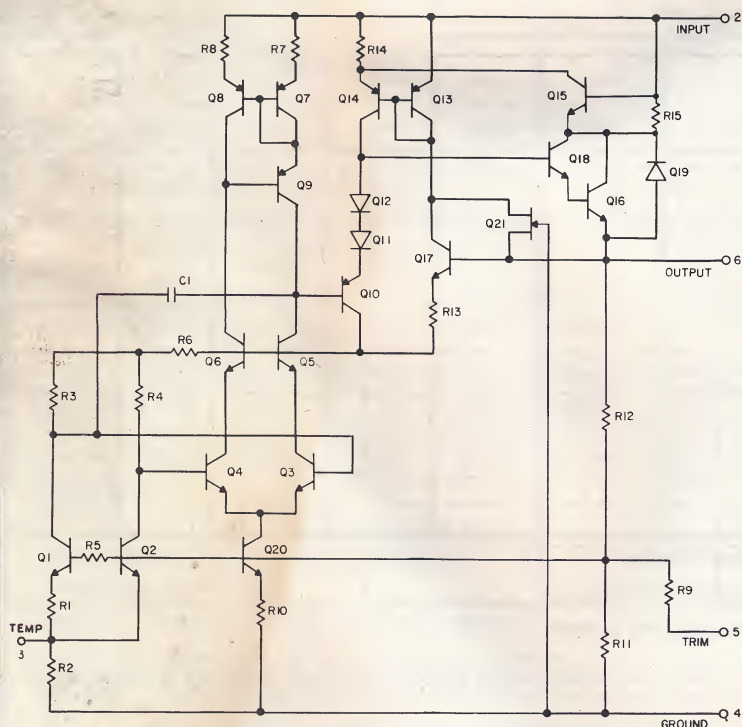
GENERAL DESCRIPTION

The REF-02 Precision Voltage Reference provides a stable +5V output which can be adjusted over a $\pm 6\%$ range with minimal effect on temperature stability. Single supply operation over an input voltage range of 7V to 40V, low current drain of 1mA, and excellent temperature stability are achieved with an improved bandgap design. Low cost, low noise and low power make the REF-02 an excellent choice whenever a stable voltage reference is required, such as in D/A and A/D converters, in portable instruments, and in digital voltmeters. The versatility of the REF-02 is illustrated by its use as a 5V, 4A regulator (see page 5) and as a monolithic thermometer. (See AN-18, "Thermometer Applications of the REF-02.") For +10V Precision Voltage References see the REF-01 data sheet.

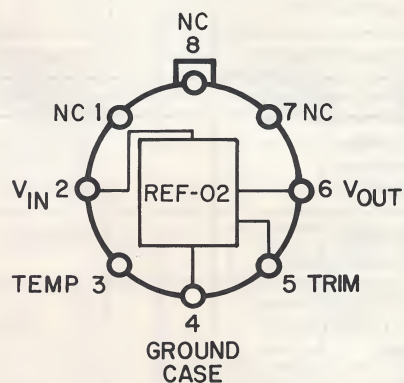
FEATURES

- Adjustable 5 Volt Output $\pm 6\%$
- Excellent Temperature Stability 3 ppm/ $^{\circ}\text{C}$
- Low Noise 10 $\mu\text{Vp-p}$
- Low Power 15mW
- Wide Input Voltage Range 7V to 40V
- High Load Driving Capability 20mA
- Temperature Voltage Output 2.1 mV/ $^{\circ}\text{C}$
- No External Components
- Short Circuit Proof
- MIL-STD-883A Screening Available

SIMPLIFIED SCHEMATIC



PIN CONNECTIONS AND ORDERING INFORMATION



TO-99 (J-Suffix)

ORDER: REF-02AJ
REF-02J
REF-02EJ
REF-02HJ
REF-02CJ

Military Temperature Range Devices
with MIL-STD-883A Class B Processing:

ORDER: REF02-883-AJ
REF02-883-J

The premium performance of this product is achieved through an advanced processing technology. All Precision Monolithics products are guaranteed to meet or exceed published specifications.

TECHNICAL SPECIFICATIONS SEPTEMBER 1976

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ABSOLUTE MAXIMUM RATINGS

Input Voltage REF-02, A, E, H	40 V	Operating Temperature Range	
REF-02C	30 V	REF-02A, REF-02	-55°C to +125°C
Power Dissipation (see note)	500mW	REF-02E, REF-02H, REF-02C	0°C to +70°C
Output Short Circuit Duration (to ground or V_{IN})	Indefinite		
Storage Temperature Range	-65°C to +150°C	Note:	Derate at 7.1mW/°C above 80°C ambient temperature.
Lead Temperature (Soldering, 60 sec)	300°C		

ELECTRICAL CHARACTERISTICS

			REF-02A			REF-02			
These specifications apply for $V_{IN} = +15V$, $T_A = 25^{\circ}C$, unless otherwise noted.									
Parameter	Symbol	Test Conditions	Min	Typ	Max	Min	Typ	Max	Units
Output Voltage	V_O	$I_L = 0$	4.985	5.000	5.015	4.975	5.000	5.025	V
Output Adjustment Range	ΔV_{trim}	$R_P = 10k\Omega$	± 3.0	± 6.0	—	± 3.0	± 6.0	—	%
Output Voltage Noise	e_{np-p}	0.1Hz to 10Hz (Note 1)	—	10	15	—	10	15	μV_{p-p}
Input Voltage Range	V_{IN}		7	—	40	7	—	40	V
Line Regulation (Note 2)		$V_{IN} = 8$ to 33V	—	0.006	0.010	—	0.006	0.010	%/V
Load Regulation (Note 2)		$I_L = 0$ to 10mA	—	0.005	0.008	—	0.006	0.010	%/mA
Turn-on Settling Time	t_{on}	To $\pm 0.1\%$ of final value	—	5.0	—	—	5.0	—	μsec
Quiescent Current	I_{SY}	No Load	—	1.0	1.4	—	1.0	1.4	mA
Load Current	I_L		10	21	—	10	21	—	mA
Sink Current	I_S		-0.3	-0.5	—	-0.3	-0.5	—	mA
Short Circuit Current	I_{SC}	$V_O = 0$	—	30	—	—	30	—	mA
Temp Voltage Output	V_T	(Note 3)	—	630	—	—	630	—	mV

The following specifications apply for $V_{IN} = +15V$, $-55^\circ C \leq T_A \leq +125^\circ C$, unless otherwise noted.

Output Voltage Change with Temperature (Notes 4 and 5)	ΔV_{OT}	$0^\circ \leq T_A \leq +70^\circ C$	—	0.02	0.06	—	0.07	0.17	%
		$-55^\circ \leq T_A \leq +125^\circ C$	—	0.06	0.15	—	0.18	0.45	%
Output Voltage Temperature Coefficient	TCV_O	(Note 6)	—	3	8.5	—	10	25	ppm/°C
Change in V_O Temperature Coefficient with Output Adjustment		$R_P = 10k\Omega$	—	0.7	—	—	0.7	—	ppm/%
Line Regulation ($V_{IN} = 8$ to 33V) (Note 2)		$0^\circ \leq T_A \leq +70^\circ C$	—	0.007	0.012	—	0.007	0.012	%/V
		$-55^\circ \leq T_A \leq +125^\circ C$	—	0.009	0.015	—	0.009	0.015	%/V
Load Regulation ($I_L = 0$ to 8mA) (Note 2)		$0^\circ \leq T_A \leq +70^\circ C$	—	0.006	0.010	—	0.007	0.012	%/mA
		$-55^\circ \leq T_A \leq +125^\circ C$	—	0.007	0.012	—	0.009	0.015	%/mA
Temp Voltage Output Temperature Coefficient	TCV_T	(Note 3)	—	2.1	—	—	2.1	—	mV/°C

NOTE 1: Parameter is not 100% tested; 90% of units meet this specification.

NOTE 2: Line and Load Regulation specifications include the effects of self heating.

NOTE 3: Limit current in or out of pin 3 to 50nA and capacitance on pin 3 to 30pF.

NOTE 4: ΔV_{OT} is defined as the absolute difference between the maximum output voltage and minimum output voltage over the specified temperature range expressed as a percentage of 5V:

$$\Delta V_{OT} = \frac{V_{MAX} - V_{MIN}}{5V} \times 100$$

NOTE 5: ΔV_{OT} specification applies trimmed to 5.000V or untrimmed.

NOTE 6: TCV_O is defined as ΔV_{OT} divided by the temperature range; i.e., $TCV_O (0^\circ \text{ to } +70^\circ C) = \frac{\Delta V_{OT} 0^\circ \text{ to } +70^\circ C}{70^\circ C}$

and $TCV_O (-55^\circ \text{ to } +125^\circ C) = \frac{\Delta V_{OT} -55^\circ \text{ to } +125^\circ C}{180^\circ C}$

REF-02 DEFINITIONS

LINE REGULATION

The ratio of the change in output voltage to the change in line voltage producing it.

LOAD REGULATION

The ratio of the change in output voltage to the change in load current-producing it.

QUIESCENT CURRENT (I_{SY})

The current required from the supply to operate the device with no load.

OUTPUT TURN-ON SETTLING TIME (t_{on})

The time required for the output voltage to reach its final value within a specified error band after application of V_{IN}

OUTPUT VOLTAGE NOISE (e_{np-p})

The peak to peak output noise voltage in a specified frequency band.

OUTPUT CHANGE WITH TEMPERATURE (ΔV_{OT})

The absolute difference between the maximum output voltage and the minimum output voltage over the specified temperature range expressed as a percentage of 5V:

$$\Delta V_{OT} = \frac{V_{MAX} - V_{MIN}}{5V} \times 100$$

OUTPUT TEMPERATURE COEFFICIENT (TCV_O)

The ratio of the output change with temperature to the specified temperature range expressed in ppm/ $^{\circ}C$.

ELECTRICAL CHARACTERISTICS

			REF-02E			REF-02H			REF-02C			
These specifications apply for $V_{IN} = +15V$, $T_A = 25^{\circ}C$, unless otherwise noted.												
Parameter	Symbol	Test Conditions	Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	Units
Output Voltage	V_O	$I_L = 0$	4.985	5.000	5.015	4.975	5.000	5.025	4.950	5.000	5.050	V
Output Adjustment Range	ΔV_{trim}	$R_p = 10k\Omega$	± 3.0	± 6.0	—	± 3.0	± 6.0	—	± 2.7	± 6.0	—	%
Output Voltage Noise	e_{np-p}	0.1Hz to 10Hz (Note 1)	—	10	15	—	10	15	—	12	18	μV_{p-p}
Input Voltage Range	V_{IN}		7	—	40	7	—	40	7	—	30	V
Line Regulation (Note 2)		$V_{IN} = 8$ to 33V	—	0.006	0.010	—	0.006	0.010	—	—	—	%/V
		$V_{IN} = 8$ to 30V	—	—	—	—	—	—	—	0.009	0.015	%/V
Load Regulation (Note 2)		$I_L = 0$ to 10 mA	—	0.005	0.008	—	0.006	0.010	—	—	—	%/mA
		$I_L = 0$ to 8 mA	—	—	—	—	—	—	—	0.006	0.015	%/mA
Turn-on Settling Time	t_{on}	To $\pm 0.1\%$ of final value	—	5.0	—	—	5.0	—	—	5.0	—	μsec
Quiescent Current	I_{SY}	No Load	—	1.0	1.4	—	1.0	1.4	—	1.0	1.6	mA
Load Current	I_L		10	21	—	10	21	—	8	21	—	mA
Sink Current	I_S		-0.3	-0.5	—	-0.3	-0.5	—	-0.2	-0.5	—	mA
Short Circuit Current	I_{SC}	$V_O = 0$	—	30	—	—	30	—	—	30	—	mA
Temp Voltage Output	V_T	(Note 3)	—	630	—	—	630	—	—	630	—	mV

The following specifications apply for $V_{IN} = +15V$, $0^{\circ}C \leq T_A \leq +70^{\circ}C$, unless otherwise noted.

Output Voltage Change with Temperature	ΔV_{OT}	(Notes 4 and 5)	—	0.02	0.06	—	0.07	0.17	—	0.14	0.45	%
Output Voltage Temperature Coefficient	TCV_O	(Note 6)	—	3	8.5	—	10	25	—	20	65	ppm/ $^{\circ}C$
Change in V_O Temperature Coefficient With Output Adjustment		$R_p = 10k\Omega$	—	0.7	—	—	0.7	—	—	0.7	—	ppm/%
Line Regulation (Note 2)		$V_{IN} = 8$ to 33V	—	0.007	0.012	—	0.007	0.012	—	—	—	%/V
		$V_{IN} = 8$ to 30V	—	—	—	—	—	—	—	0.011	0.018	%/V
Load Regulation (Note 2)		$I_L = 0$ to 8 mA	—	0.006	0.010	—	0.007	0.012	—	—	—	%/mA
		$I_L = 0$ to 5 mA	—	—	—	—	—	—	—	0.008	0.018	%/mA
Temp Voltage Output Temperature Coefficient	TCV_T	(Note 3)	—	2.1	—	—	2.1	—	—	2.1	—	mV/ $^{\circ}C$

NOTE 1: Parameter is not 100% tested; 90% of units meet this specification.

NOTE 2: Line and Load Regulation specifications include the effects of self heating.

NOTE 3: Limit current in or out of pin 3 to 50nA and capacitance on pin 3 to 30pF.

NOTE 4: ΔV_{OT} is defined as the absolute difference between the maximum output voltage and the minimum output voltage over the specified temperature range expressed as a percentage of 5V:

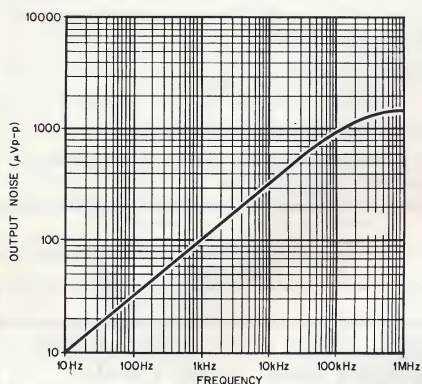
$$\Delta V_{OT} = \frac{V_{MAX} - V_{MIN}}{5V} \times 100$$

NOTE 5: ΔV_{OT} specification applies trimmed to +5.000V or untrimmed.

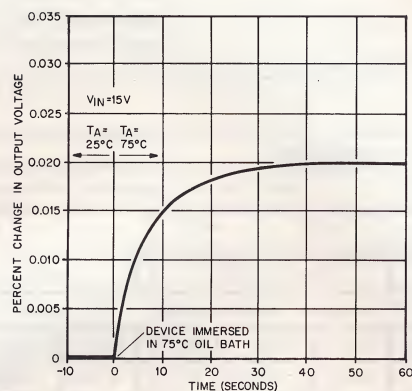
NOTE 6: TCV_O is defined as ΔV_{OT} divided by the temperature range; i.e., $TCV_O = \frac{\Delta V_{OT}}{70^{\circ}C}$

TYPICAL PERFORMANCE CURVES

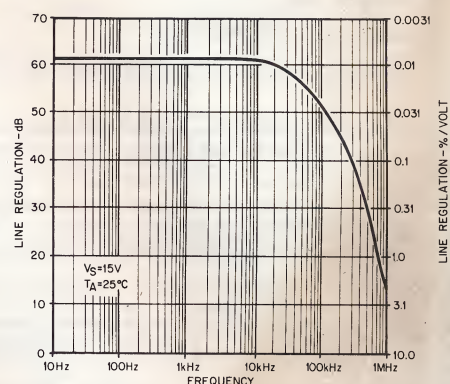
OUTPUT WIDEBAND
NOISE VS BANDWIDTH
(.1 Hz TO FREQUENCY INDICATED)



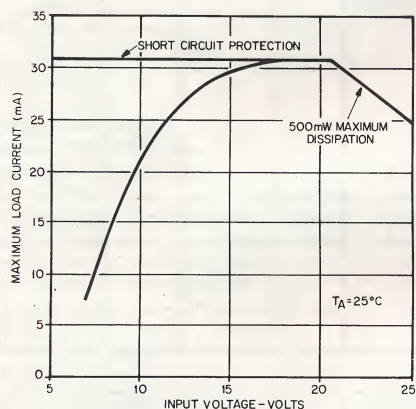
OUTPUT CHANGE DUE
TO THERMAL SHOCK



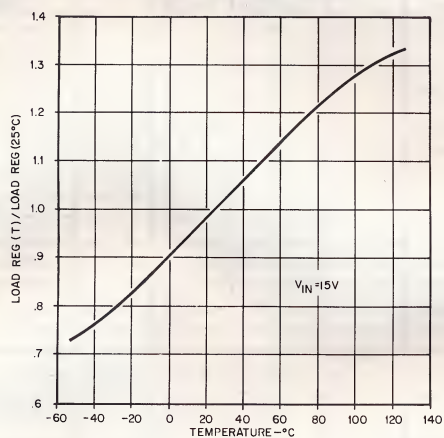
LINE REGULATION
VS FREQUENCY



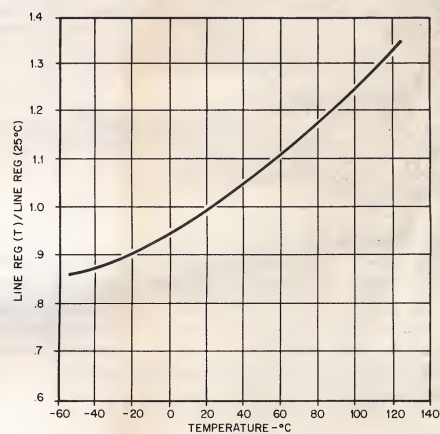
MAXIMUM LOAD CURRENT
VS INPUT VOLTAGE



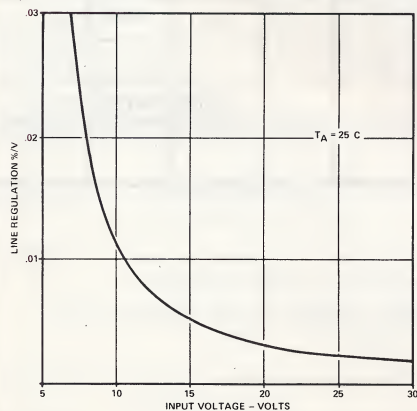
NORMALIZED LOAD
REGULATION ($\Delta I_L = 10\text{mA}$)
VS TEMPERATURE



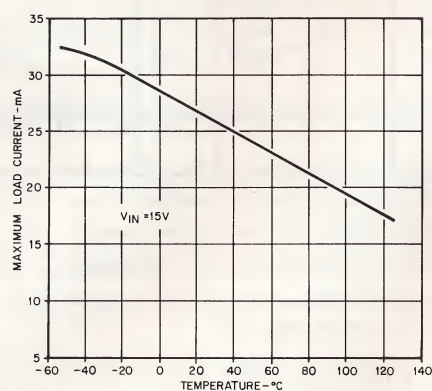
NORMALIZED LINE REGULATION
VS TEMPERATURE



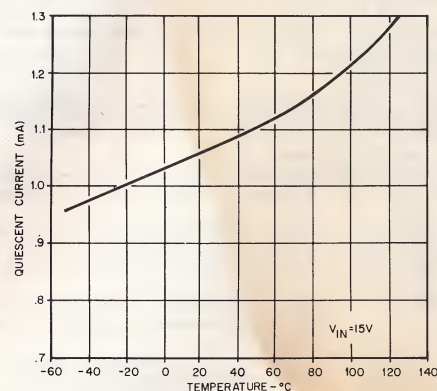
LINE REGULATION
VS SUPPLY VOLTAGE



MAXIMUM LOAD CURRENT
VS TEMPERATURE



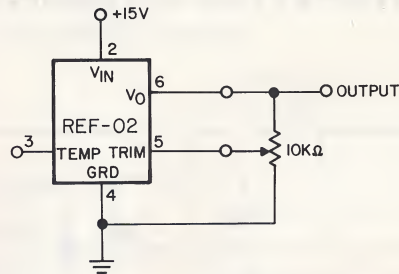
QUIESCENT CURRENT
VS TEMPERATURE



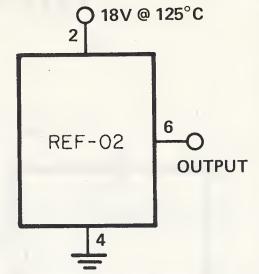
OUTPUT ADJUSTMENT

The REF-02 trim terminal can be used to adjust the output voltage over a $5V \pm 300mV$ range. This feature allows the system designer to trim system errors by setting the reference to a voltage other than 5V. Of course, the output can also be set to exactly 5.000V, or to 5.12V for binary applications.

Adjustment of the output does not significantly affect the temperature performance of the device. Typically the temperature coefficient change is $0.7 \text{ ppm}/^{\circ}\text{C}$ for 100mV of output adjustment.



BURN-IN CIRCUIT



TYPICAL APPLICATIONS

OUTPUT POWER BOOSTING – 5 VOLT 4 AMP PRECISION REGULATOR

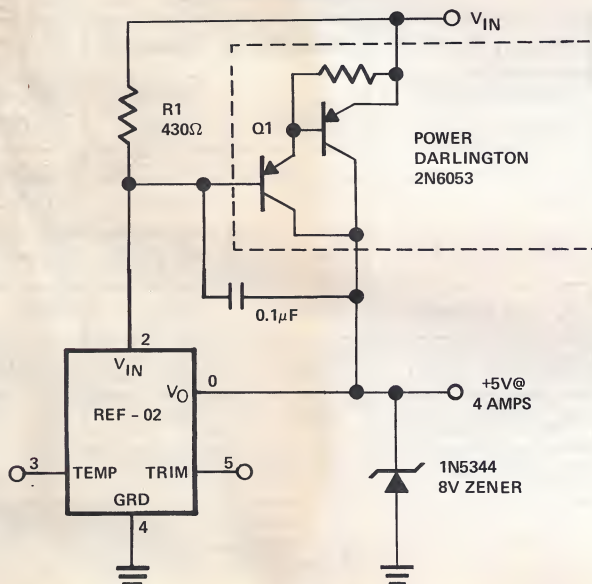
THEORY OF OPERATION

With no output load, the voltage across R1 is determined by the REF-02's typical supply current of 1mA. With an output load, Q1 turns on and provides most of the load current. The total current that the REF-02 must supply is the base current of Q1 and approximately 4mA through R1.

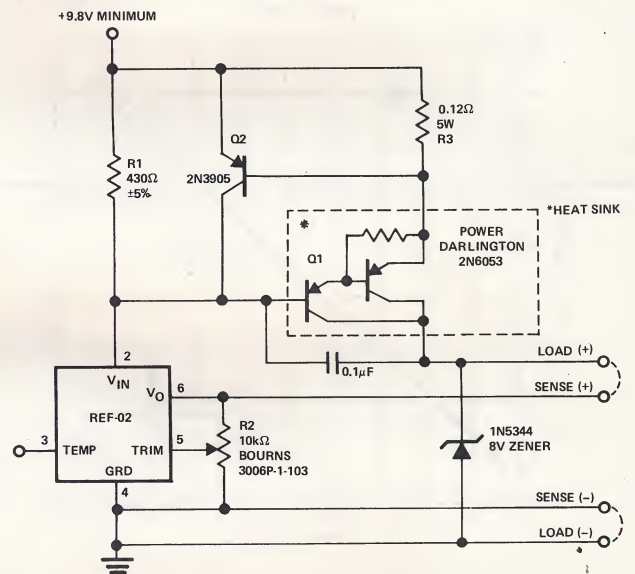
Both current limiting and remote sensing may be added using the circuitry shown below. Since untrimmed output accuracy

depends on the grade of REF-02 selected, an optional trimming potentiometer may be used to adjust the output to exactly 5.000V. The voltage drop across R3 at 5 amps causes Q2 to turn on and remove the base current for Q1. A zener diode is recommended as shown to prevent latch-up under certain transient load conditions.

BASIC REGULATOR

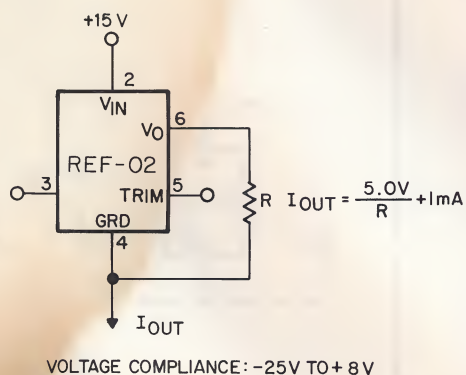


ADJUSTABLE PRECISION +5V @4A REGULATOR WITH CURRENT LIMITING AND REMOTE SENSING

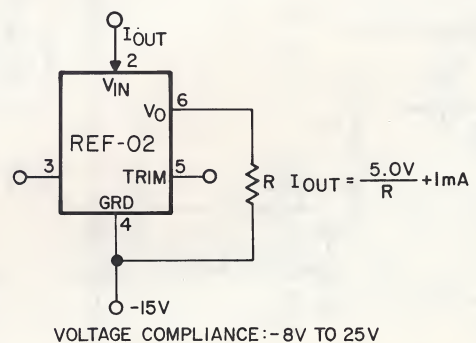


FOR COMPLETE THEORY OF OPERATION AND TYPICAL PERFORMANCE SPECIFICATIONS, SEE AN-20, "PRECISION 5 VOLT AND 10 VOLT REGULATORS WITH 4 AMP OUTPUT."

CURRENT SOURCE

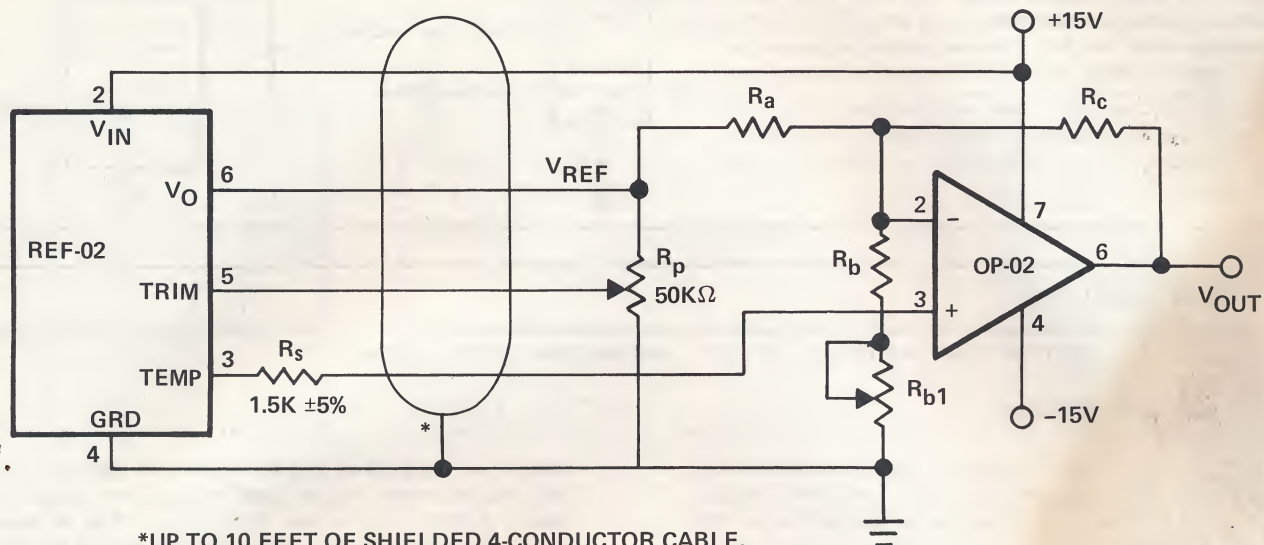


CURRENT SINK



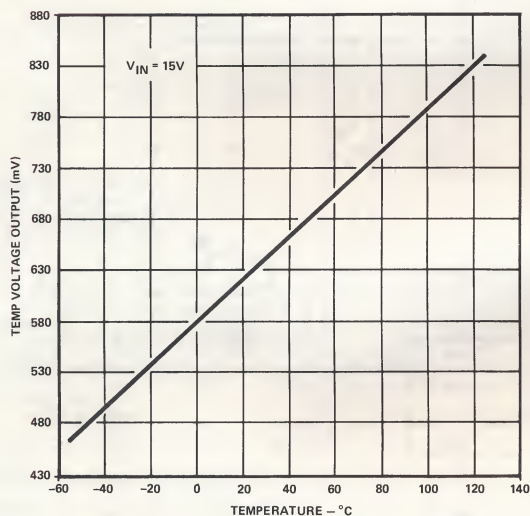
TYPICAL APPLICATIONS

PRECISION TEMPERATURE TRANSDUCER WITH REMOTE SENSOR



*UP TO 10 FEET OF SHIELDED 4-CONDUCTOR CABLE.

TYPICAL TEMPERATURE VOLTAGE
OUTPUT VS TEMPERATURE
(REF-02A)



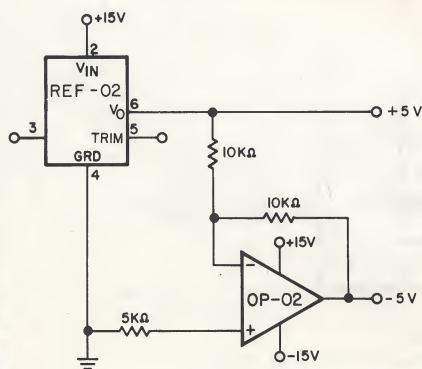
RESISTOR VALUES

TCV _{OUT} SLOPE (S)	10mV/°C	100mV/°C	10mV/°F
TEMPERATURE RANGE	-55° to +125°C	-55° to +125°C	-67°F to +257°C
OUTPUT VOLTAGE RANGE	-0.55V to +1.25V	-5.5V to +12.5V*	-0.67V to +2.57V
ZERO SCALE	0V @ 0°C	0V @ 0°C	0V @ 0°F
R _a (±1% resistor)	9.09KΩ	15KΩ	7.5KΩ
R _{b1} (±1% resistor)	1.5KΩ	1.82KΩ	1.21KΩ
R _{bp} (Potentiometer)	200Ω	500Ω	200Ω
R _c (±1% resistor)	5.11KΩ	84.5KΩ	8.25KΩ

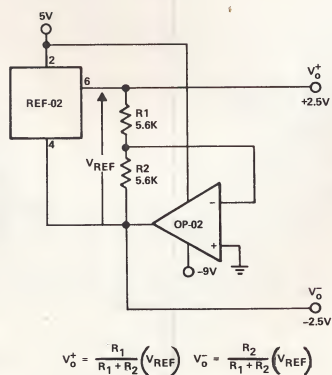
*For 125°C operation, the op amp output must be able to swing to +12.5V; increase V_{IN} to +18V from +15V if this is a problem.

FOR THEORY OF OPERATION AND CALIBRATION PROCEDURE CONSULT APPLICATION NOTE AN-18, "THERMOMETER APPLICATIONS OF THE REF-02."

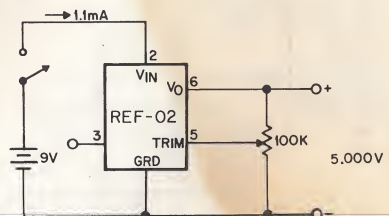
±5V REFERENCE



±2.5V REFERENCE



PRECISION CALIBRATION STANDARD

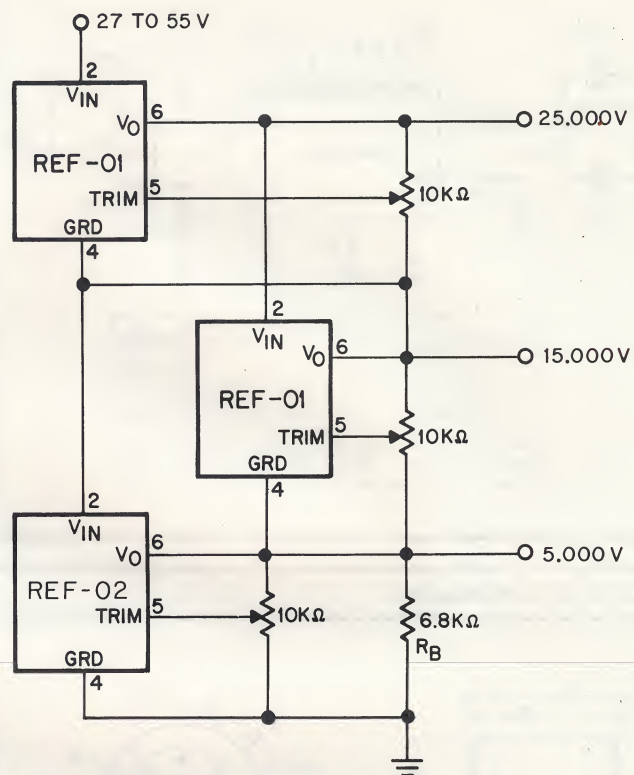


TYPICAL APPLICATIONS

PRECISION CURRENT SOURCE

Two REF-01's and one REF-02 can be stacked to yield 5,000, 15,000 and 25,000V outputs. An additional advantage is near-perfect line regulation of the 5,000 and 15,000 output voltages. A 27V to 55V input change produces an output change which is less than the noise voltage of the devices. A load bypass resistor (R_B) provides a path for the supply current (I_{SY}) of the 15,000V regulator.

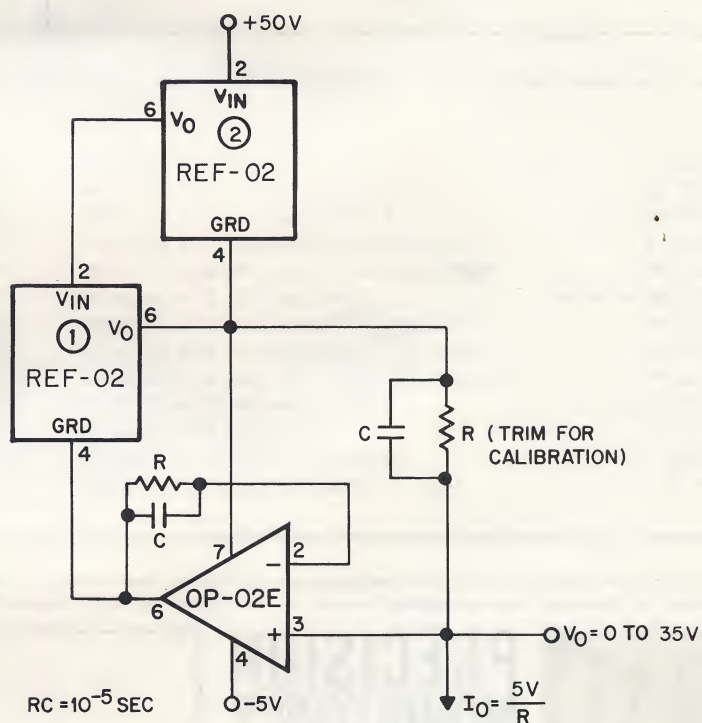
In general any number of REF-01's and REF-02's can be stacked this way. For example, ten devices will yield ten outputs in 5 or 10V steps. The line voltage can range from 100 to 130V. However, care must be taken to ensure that the total load currents do not exceed the maximum usable current (typically 21mA).



REFERENCE STACK WITH EXCELLENT LINE REGULATION

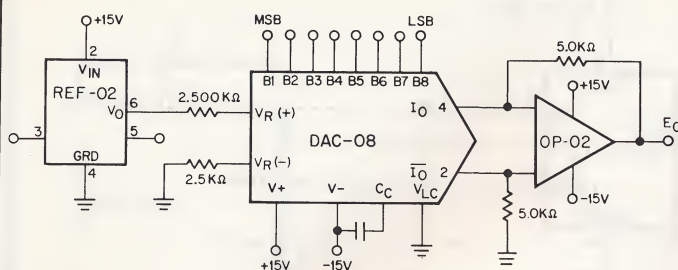
A current source with 35V output compliance and excellent output impedance can be obtained using this circuit. REF-02 ② keeps the line voltage and power dissipation constant in device ①; the only important error consideration at room temperature is the negative supply rejection of the op amp. The typical $3\mu\text{V/V}$ PSRR of the OP-02E will create a 20 ppm change ($3\mu\text{V/V} \times 35\text{V}/5\text{V}$) in output current over a 35V range; for example, a 5mA current source can be built ($R = 1\text{k}\Omega$) with 350 M Ω output impedance:

$$R_O = \left(\frac{35V}{20 \times 10^{-6} \times 5mA} \right)$$

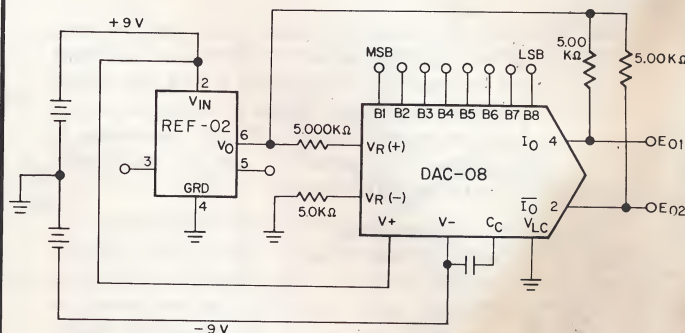


TYPICAL APPLICATIONS

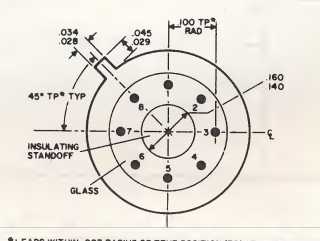
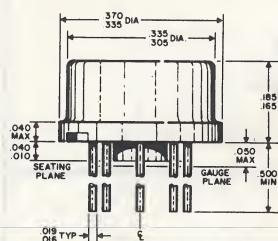
D/A CONVERTER REFERENCE



	B1	B2	B3	B4	B5	B6	B7	B8	E0
POS FULL SCALE	1	1	1	1	1	1	1	1	+9.920
POS FULL SCALE-LSB	1	1	1	1	1	1	1	0	+9.840
(+) ZERO SCALE	1	0	0	0	0	0	0	0	+0.040
(-) ZERO SCALE	0	1	1	1	1	1	1	1	-0.040
NEG FULL SCALE+LSB	0	0	0	0	0	0	0	1	-9.840
NEG FULL SCALE	0	0	0	0	0	0	0	0	-9.920

BATTERY OPERATED
D/A CONVERTER REFERENCE

PACKAGE DIMENSIONS

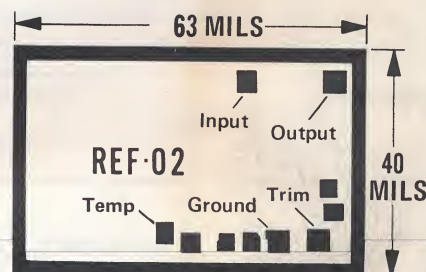


*LEADS WITHIN .007 RADIUS OF TRUE POSITION (TP) AT GAUGE PLANE

Note: Dimensions in inches unless otherwise noted.

TO-99 (J)

CHIP DIMENSIONS



For other related Precision Monolithics, Inc. components, see the following data sheets:

DAC-01 6 Bit D/A Converter
 DAC-02 8-10 Bit Plus Sign D/A Converter
 DAC-03 8-10 Bit Low Cost D/A Converter
 DAC-04 8-10 Bit Two's Complement D/A Converter
 DAC-08 High Speed Multiplying 8 Bit D/A Converter
 SSS1508A/1408A Low Cost 8 Bit D/A Converter
 DAC-76 COMDACTM Companding D/A Converter
 DAC-86 COMDACTM Bell μ -255 Law D/A Converter
 DAC-77 COMDACTM CCITT "A" Law D/A Converter
 DAC-100 8-10 Bit Low Cost D/A Converter
 AD-02 High Speed A/D Converter
 OP-01 High Speed Operational Amplifier
 OP-02 High Performance Operational Amplifier

OP-04 Dual Matched High Performance Operational Amplifier
 OP-05 Low Noise, Low Drift Compensated Op Amp
 OP-07 Ultra Low Offset Voltage Op Amp
 OP-10 Dual Matched Instrumentation Operational Amplifier
 OP-14 Dual Matched High Performance Operational Amplifier
 SSS725 Low Noise, Low Drift Instrumentation Op Amp
 SSS741 Internally Compensated Operational Amplifier
 SSS747 Dual Internally Compensated Operational Amplifier
 CMP-01 Fast Precision Comparator
 CMP-02 Low Input Current Precision Comparator
 MAT-01 Ultra Matched Dual Transistor
 REF-01 +10V Precision Voltage Reference
 REF-02 +5V Precision Voltage Reference

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Application Notes

AN-18

THERMOMETER APPLICATIONS OF THE REF-02

by
George Erdi

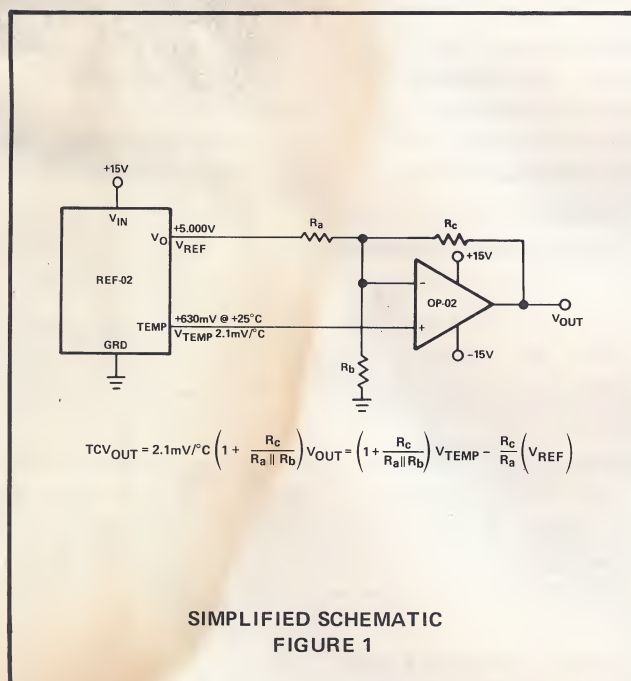
INTRODUCTION

This application note describes electronic thermometer applications of the REF-02 +5V Voltage Reference where the voltage output is a direct measurement of temperature in °C or in °F. These applications use the predictable 2.1mV/°C TEMP output voltage temperature coefficient of the REF-02, a byproduct of a bandgap voltage reference design. Thermometer applications are described first followed by a discussion of bandgap voltage reference theory.

THERMOMETER ESSENTIALS

In addition to a highly linear temperature sensitive component, electronic thermometers should have the following characteristics:

- 1) Convenient scaling such as 10mV/°C, 100mV/°C, or 10mV/°F.
- 2) Direct voltage readings such as -0.55V at -55°C, 0V at 0°C, and +1.25V at +125°C.
- 3) Room temperature calibration.



BASIC CIRCUIT IMPLEMENTATION

The simplified schematic in Fig. 1 shows the basic thermometer connections. An operational amplifier, three resistors, and the +5.000V output of the REF-02 function together to level shift and amplify VTEMP allowing VOUT to read in the desired manner. The expression for VOUT is:

$$\text{Eq. 1) } V_{OUT} = \left(1 + \frac{R_C}{R_A \parallel R_B} \right) V_{TEMP} - \frac{R_C}{R_A} (V_{REF})$$

The first term is the gain of the circuit with VREF equal to 0V; the second term is the gain of the circuit with VTEMP equal to 0V. Differentiating Eq. 1 with respect to temperature gives the slope, S, of the output-versus-temperature curve:

$$\begin{aligned} \text{Eq. 2) } \frac{dV_{OUT}}{dT} &= S = m \left(1 + \frac{R_C}{R_A \parallel R_B} \right) \\ &= 2.1\text{mV/}^\circ\text{C} \left(1 + \frac{R_C}{R_A \parallel R_B} \right) \end{aligned}$$

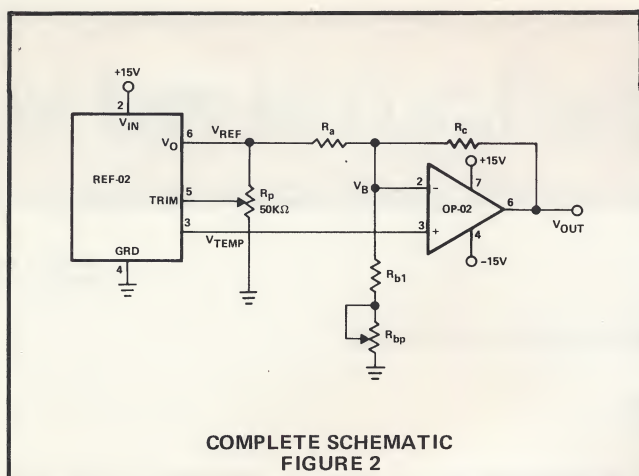
where $m = \text{TCV}_{TEMP}$

Thus, the ratio of R_C to $R_A \parallel R_B$ sets the slope of VOUT, and the ratio of R_C to R_A and VREF set the initial output value at 25°C. Table I lists typical scaling ratios for different output scales

TEMPERATURE SCALING RATIOS

$V_{REF} = 5.000\text{V}$, $V_{TEMP} = 630\text{mV @ } 25^\circ\text{C}$, $\text{TCV}_{TEMP} = 2.1\text{mV/}^\circ\text{C}$			
$V_{OUT @ 25^\circ\text{C}}$ (77°F)	TCV_{OUT} (Slope)	$\frac{R_C}{R_A}$	$\frac{R_C}{R_A \parallel R_B}$
250mV	10mV/°C	0.55	3.76
2.5V	100mV/°C	5.50	46.6
770mV	10mV/°F	0.926	7.57

TABLE I



COMPLETE CIRCUIT

Two potentiometers, R_p and R_{bp} , have been added to the circuit for precise calibration and to allow for the $\pm 1\%$ resistor tolerances. V_{REF} is adjusted by R_p to set the V_{OUT} value at $+25^\circ\text{C}$ (77°F); the ratio of R_c to $R_a \parallel R_b$ is adjusted by R_{bp} to set the slope of V_{OUT} versus temperature. Resistor values for typical output scales are shown in Table II.

RESISTOR VALUES

TCV _{OUT} SLOPE (S)	10mV/ $^\circ\text{C}$	100mV/ $^\circ\text{C}$	10mV/ $^\circ\text{F}$
TEMPERATURE RANGE	-55° to $+125^\circ\text{C}$	-55° to $+125^\circ\text{C}$	-67°F to $+257^\circ\text{F}$
OUTPUT VOLTAGE RANGE	-0.55V to $+1.25\text{V}$	-5.5V to $+12.5\text{V}^*$	-0.67V to $+2.57\text{V}$
ZERO SCALE	0V @ 0°C	0V @ 0°C	0V @ 0°F
R_a ($\pm 1\%$ resistor)	9.09K Ω	15K Ω	7.5K Ω
R_{b1} ($\pm 1\%$ resistor)	1.5K Ω	1.82K Ω	1.21K Ω
R_{bp} (Potentiometer)	200 Ω	500 Ω	200 Ω
R_c ($\pm 1\%$ resistor)	5.11K Ω	84.5K Ω	8.25K Ω

*For 125°C operation, the op amp output must be able to swing to $+12.5\text{V}$; increase V_{IN} to $+18\text{V}$ from $+15\text{V}$ if this is a problem.

TABLE II

CALIBRATION CONDITIONS

All calibration is conducted in free air. Heatsinking of the REF-02 is unnecessary and is undesirable. The small (2°C) rise in chip temperature of the REF-02 above ambient temperature serves as an error-cancelling factor of some second order effects internal to the REF-02 design. The calibration procedure which follows assumes free air — no heatsinking — calibration.

CALIBRATION PROCEDURE

Calibration is performed at ambient temperature with two adjustments using the following procedure:

Step 1: Measure and record V_{TEMP} and T_A in $^\circ\text{C}$.

Step 2: Calculate the calibration ratio "r" using Eq. 3:

$$\text{Eq. 3) } r \equiv \frac{R_a \parallel R_b}{R_c + R_a \parallel R_b} = \frac{V_{TEMP} \text{ in mV}}{S(T_A + 273)}$$

Where $S = \text{TCV}_{OUT}$, T_A = ambient temperature in $^\circ\text{C}$

Step 3: Turn power off, short V_{REF} terminal to ground, and apply a precise 100mV to the V_{OUT} terminal.

Step 4: Adjust R_{bp} so that $V_B = r(100\text{mV})$; remove short.

Step 5: Turn power on; adjust R_p so that V_{OUT} equals the correct value at ambient temperature.

The system is now calibrated.

CALIBRATION EXAMPLE

Here is an example at $T_A = 25^\circ\text{C}$, $S = 10\text{mV}/^\circ\text{C}$, and $V_{TEMP} = 632\text{mV}$:

Step 1: $V_{TEMP} = 632\text{mV}$, $T_A = 25^\circ\text{C}$,

Step 2: Using Eq. 3:

$$r = \frac{V_{TEMP}}{S(T_A + 273)} = \frac{632}{10(25 + 273)} = \frac{632}{2980} = 0.2121$$

Step 3: Apply 100.00mV to V_{OUT} with power off and V_{REF} connected to ground.

Step 4: Adjust R_{bp} so that $V_B = r(100\text{mV}) = 21.21\text{mV}$

Step 5: Turn power on and adjust R_p so that V_{OUT} equals $+0.25\text{V}$.

The system is now calibrated.

TRANSDUCER ERROR FACTORS

Error terms are threefold:

1. Slope errors — Deviations from nominal slope. For example, if the slope is $10.04\text{mV}/^\circ\text{C}$ instead of $10.00\text{mV}/^\circ\text{C}$, the accuracy due to the slope error is 0.4%.
2. Linearity errors — Deviations in V_{TEMP} versus temperature from straight line performance, a change in V_{TEMP} slope with temperature.
3. Offset error — V_{OUT} deviations due to changes in V_{REF} with temperature.

Since these errors are grade dependent, Table III is provided as an aid in specifying the correct combination of components for a given application. Offset error can be eliminated by using one REF-02 as a temperature sensor only and another REF-02 (operated at a constant temperature) as V_{REF} .

TRANSDUCER PERFORMANCE

Typical system accuracy is $\pm 0.5\%$ over the -55° to $+125^\circ\text{C}$ range of a REF-02A. For example, when calibrated at $+25^\circ\text{C}$, the reading of V_{OUT} at $+105^\circ\text{C}$ may be 105.4°C , a deviation of 0.5% of the 80° temperature change ($+25^\circ\text{C}$ to $+105^\circ\text{C}$).

Although the REF-02 is guaranteed to perform over the -55° to $+125^\circ\text{C}$ range only, operation beyond those limits is possible. A large number of devices were measured and found to be functioning satisfactorily over the -150°C to $+170^\circ\text{C}$ range, and there was only a slight degradation in accuracy.

REMOTE APPLICATIONS

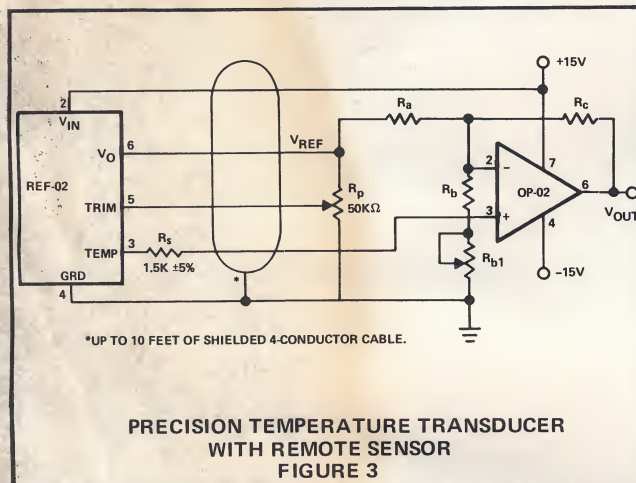
In many applications, the sensor must be located some distance away from the measurement circuitry. One precaution must be taken with the REF-02: a 1.5K Ω resistor

should be connected between pin 3 (TEMP) and its associated cable conductor to isolate this pin from cable capacitances. Remote application of the transducer is illustrated in Fig. 3 with R_s , the isolation resistor.

TYPICAL TRANSDUCER PERFORMANCE VS. GRADE

GRADE PARAMETER	REF-02A	REF-02	REF-02E	REF-02H	REF-02C
TEMPERATURE RANGE	-55° to +125°C	-55° to +125°C	0° to +70°C	0° to +70°C	0° to +70°C
SLOPE ERROR	±0.30%	±0.40%	±0.25%	±0.35%	±0.45%
TCVTEMP ERROR	±0.10%	±0.12%	±0.08%	±0.10%	±0.15%
OFFSET ERROR	±0.15%	±0.40%	±0.10%	±0.30%	±0.60%
RMS ERROR SUM	±0.35%	±0.58%	±0.28%	±0.47%	±0.76%
TYPICAL ACCURACY	0.50%	0.75%	0.40%	0.60%	0.90%
OP-02 GRADE RECOMMENDED	OP-02A	OP-02	OP-02E	OP-02C	OP-02C

TABLE III

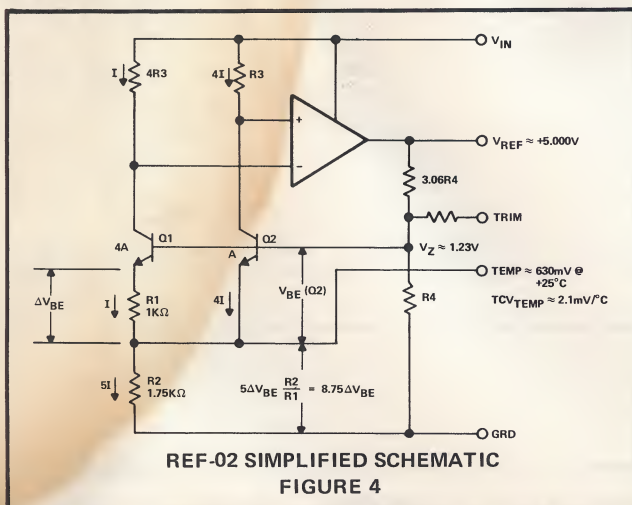


PRECISION TEMPERATURE TRANSDUCER WITH REMOTE SENSOR
FIGURE 3

TRANSDUCER SUMMARY

The accuracies indicated compare quite favorably to traditional temperature measurement methods such as thermocouples and thermistors. Ease-of-use, low cost, and high accuracy make this new bandgap method of temperature measurement attractive in a wide range of applications.

The following section describes the bandgap principle in theory and its use in the internal REF-02 design.



REF-02 SIMPLIFIED SCHEMATIC
FIGURE 4

BANDGAP REFERENCE THEORY

Bandgap voltage references [1], [2], [3], use predictable relationships from semiconductor physics to generate a constant voltage. The base-emitter voltage of a transistor (V_{BE}) has a processing and current density dependent negative temperature coefficient of about $-2.1\text{mV}/^\circ\text{C}$. Another well known relationship with a positive temperature coefficient is the difference between base-emitter voltages of two transistors operated at different current densities:

$$\text{Eq. 4) } \Delta V_{BE} = \frac{kT}{q} \log_e \left(\frac{J_2}{J_1} \right), \text{ where}$$

k = Boltzmann's constant = 1.38×10^{-23} joules/ $^\circ\text{K}$

T = absolute temperature, $^\circ\text{K}$

q = charge of an electron = 1.6×10^{-19} coulomb

J = current density

When ΔV_{BE} is amplified and added to V_{BE} , a voltage reference with zero temperature coefficient results if the sum (V_Z) of these two terms equals the linearly-extrapolated band-gap voltage of silicon (V_{go}) at 0°K or -273°C ; $V_{go} = 1.205\text{V}$. A more exact calculation, see reference [2], will show that V_Z will have zero temperature coefficient if:

$$\text{Eq. 5) } V_Z = V_{go} + \frac{kT}{q} = 1.230\text{V @ } +25^\circ\text{C}$$

The circuit in Fig. 4 generates a ΔV_{BE} of 72mV at 25°C by making the current density of Q2 16 times greater than Q1. Q2 has four times the current of Q1, and Q1 has four times the emitter area of Q2. A ΔV_{BE} of 72mV appears across $R1$ and is amplified by 8.75 (becoming the TEMP output) and is added to V_{BE} (Q2) to produce a nearly constant V_Z of 1.23V . The $-2.1\text{mV}/^\circ\text{C}$ of TCV_{BE} is cancelled by the $+2.1\text{mV}/^\circ\text{C}$ of TCV_{TEMP} ; and V_Z is amplified by 4.06 to produce an output V_{REF} of 5.000V .

REF-02 TYPICAL NODAL VOLTAGES

TEMPERATURE VOLTAGE	$T_A = -75^\circ\text{C}$ ($T_J = 200^\circ\text{K}$)	$T_A = +25^\circ\text{C}$ ($T_J = 300^\circ\text{K}$)	$T_A = +125^\circ\text{C}$ ($T_J = 400^\circ\text{K}$)
$\Delta V_{BE} = \frac{kT}{q} \log_e 16$	48mV	72mV	96mV
$V_{TEMP} = 8.75 \Delta V_{BE}$	420mV	630mV	840mV
$V_{BE} (Q2)$	810mV	600mV	390mV
$V_Z \approx V_{BE} + V_{TEMP}$	1.23V	1.23V	1.23V
$V_{REF} \approx 1 + \frac{3.06R4}{R4} \approx 4.06 V_Z$	5.00V	5.00V	5.00V

TABLE IV

CONCLUSION

The REF-02, by using a bandgap design, provides both a stable +5V reference voltage output and an additional output voltage directly proportional to temperature. Accurate electronic thermometers reading in °C or in °F can be constructed at low cost for a wide variety of temperature monitoring and controlling applications.

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APPLICATION NOTES AVAILABLE UPON REQUEST

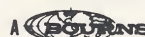
- | | |
|---|---|
| AN-6 "A Low Cost, High-Performance Tracking A/D Converter" | AN-13 "The OP-07 Ultra-Low Offset Voltage Op Amp—A Bipolar Op Amp That Challenges Choppers, Eliminates Nulling" |
| AN-10 "Simple Precision Millivolt Reference Uses No Zeners" | AN-14 "Interfacing Precision Monolithics Digital-To-Analog Converters With CMOS Logic" |
| AN-11 "A Low Cost, Easy-To-Build Successive Approximation Analog-To-Digital Converter" | AN-15 "Minimization of Noise in Operational Amplifier Applications" |
| AN-12 "Temperature Measurement Method Based On Matched Transistor Pair Requires No Reference" | AN-16 "Low Cost, High Speed Analog-To-Digital Conversion with the DAC-08" |
| | AN-17 "DAC-08 Applications Collection" |

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